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Gas Seal for DFBX HTS Current Leads

1. Requirements

1.1. Leak Rate Requirement

A seal is needed for each 7500 A HTS current lead in the DFBX to separate the 20 K helium stream from the 4 K LHe bath. The seal must be sufficiently tight to prevent 20 K gas flow from increasing the heat load on the 4 K liquid bath.

We determine the seal tightness by requiring that the heat load associated with a leak of 20 K gas be a very small fraction of the heat load due to the HTS lead. For the 7500 A lead, the specified 4K heat load shall be no greater than 0.4 W when no current is flowing in the lead, and 0.7 W at full current [1].

We require that the parasitic heat load from a 20 K gas leak into the 4K Liquid Helium bath, Q_{20K}, to satisfy:

$$Q_{20K} \leq 0.01 \text{ W}.$$

The enthalpy of helium gas at 20 K and 1.3 bar is computed from HEPAK [2] to be:

$$h_{20K,\ 1.3\ bar} = 118.4 \text{ J/g},$$

from which we determine the maximum acceptable mass flow rate at 20 K to be:

$$\dot{m}\, h_{20K,\ 1.3\ bar} \leq 0.01 \text{ W},$$

$$\dot{m} \leq 8.45 \times 10^{-5} \text{ g/sec}.$$

We use the specific volume of helium at standard conditions (1 bar & 295 K), 6.13×10^{3} cm^3/g, and convert the maximum acceptable 20 K mass flow rate to a maximum acceptable volumetric flow rate at standard conditions:

$$\dot{V} \leq 8.47 \times 10^{-5} \text{ g/sec} \times 6.13 \times 10^{3} \text{ cm}^3\text{/g}$$

$$\dot{V} \leq 0.52 \text{ std cm}^3\text{/sec}$$

1.2. Voltage Standoff Requirement

The current lead shall be capable of being raised 1500 V (DC) with respect to ground as installed in the DFBX. During this testing, the lead will be in a 300 K, 1.3 bar gaseous helium environment with the DFBX chimney at ground potential [1]. Using experimental data on the breakdown voltage in gaseous helium at room temperature shown in Figure 1 [3], one can determine that the seal should provide a spacing of about 25 mm between the lead and ground plane to allow 1.5 kV to be safely applied to the lead.

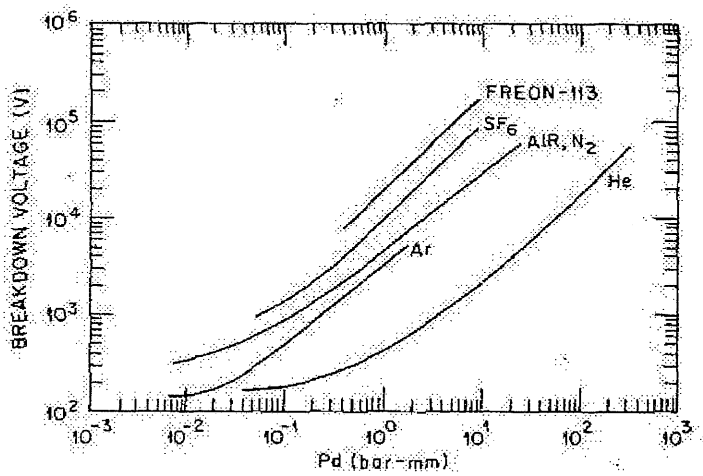


Fig. 1. Paschen curves for various gases.

1.3. Radiation Requirement

The DFBX seal will be subjected to an average annual dose of about 3 x 10^4 Gy when the machine is operated at a nominal luminosity of 10^{34} [4]. If we assume a 20-year operating lifetime at nominal luminosity, the seal material will be subjected to a total dose of 0.6 MGy. At ultimate luminosity, the dose rate will increase by a factor of 2.5 [5], so a 20-year operation at ultimate luminosity would imply a total dose of 1.5 MGy.

Candidate polymers with suitable electrical and mechanical properties with a reasonably high admissible dose include [6]:

Polyimide:	PI (e.g., Vespel)	10 MGy
Polyetheretherketone:	PEEK	50 MGy
High Density Polyethylene:	HDPE	2 MGy.

2. Seal Designs

We considered two seal designs in our study; they are described below. For each of the design types we considered two materials, PEEK and Ultra High Molecular Weight Polyethylene (UHMW-PE) as a substitute for HDPE. PI (Vespel) was not used because the raw material cost of about $7000 for one seal was considered to be too expensive. The per-seal raw material cost for PEEK is about $325, and for UHMW-PE it is about $6. As we report below, however, the UHMW-PE was found to be unsuitable since it did not allow a sufficiently leak-tight seal in our preliminary tests at 77 K.

2.1. Seal 1 - Self-Loaded Design

The seal cross section is shown in Figure 2.1-1. The sealing surfaces are the concentric surfaces with the 32 finish. In this design, the force on the sealing surfaces is provided by the elastic deformation of the 2-inch-long vertical legs. The outer diameter of the seal is dimensioned with enough interference at room temperature such that at operating temperature a 0.005 inch (200 microns) radial interference is maintained. At the inner diameter a clearance at room temperature becomes a 0.005 inch (200 micron) interference at operating temperature.

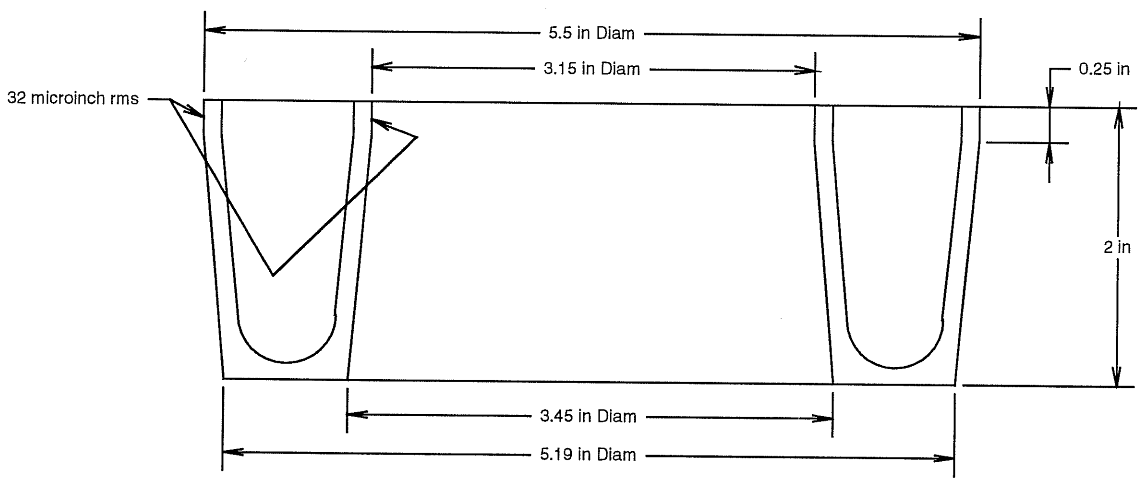


Figure 2.1-1. Seal 1 Cross Section

The attractive feature of this seal is that all loading is done by the seal itself and we do not have to worry about bellows and Belleville washers, etc at room temperature to maintain the load on the seal surface.

However, the bad feature of this seal is that it does not seal, either at room temperature or at operating temperature, since it appears to be extremely sensitive to manufacturing and assembly tolerances.

2.2. Seal 2 - Externally Loaded Design

The cross section of seal 2 is shown in Figure 2.2-1. It is intended to seal between two flat surfaces, and the actual sealing interfaces are the half – round features on the top and bottom sides. The sealing force is provided by bolts acting through a stack of Belleville spring washers to maintain a suitable load when the seal is cooled to operating temperature. The integrated thermal contraction of PEEK from 293 to 4 K is 0.01 in/in [6]; relative to austenitic stainless steel it is 0.007 in/in. (The 1.25 inch dimension will shrink by about 0.0088 inch relative to stainless steel.) For High Density Polyethylene, the integrated thermal contraction from 293 to 4 K is 0.021 in/in [6]; relative to austenitic stainless steel it is 0.018 in/in. (The 1.25 inch dimension will shrink by about 0.022 inch relative to stainless steel.)

The UHMW-PE seal used in the testing was machined from an extruded solid cylinder and the PEEK seal was machined from a cast cylinder.

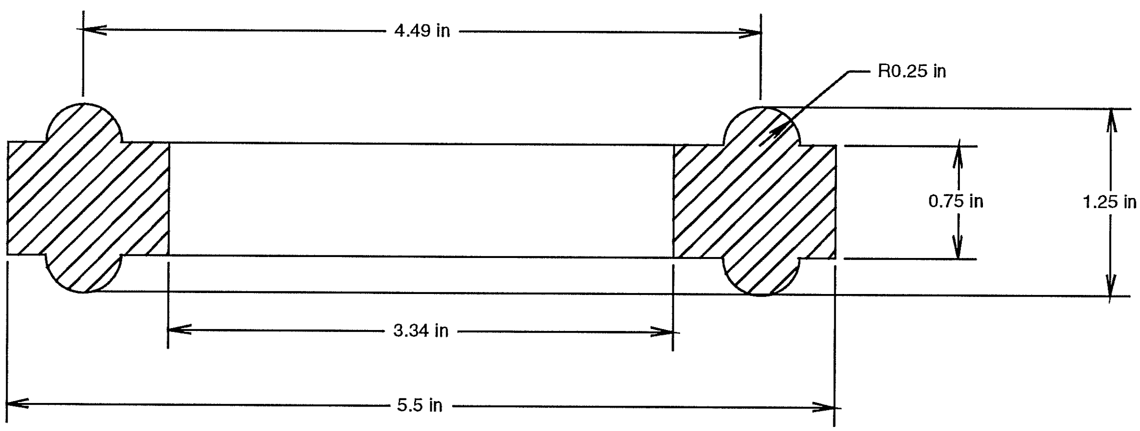


Figure 2.2-1 Seal 2 Cross Section

3. Test Results

3.1. Seal 1 Test Results

A test rig to simulate seal 1 in the DFBX was designed and fabricated, as shown in Figure 3.1-1. The PEEK seal was installed and cooled to LN temperature. We made several modifications to the test procedure, coatings of vacuum grease, and even modified the sealing surface, but the lowest flow rate we observed using a small rotameter was 8 atm-cm^3/sec (air), or about 32 atm-cm^3/sec (helium). The seal made from UHMW-PE did not seal any better.

Several reasons for the lack of sealing and possible solutions could be imagined, but we decided to abandon this approach and adopt a more straightforward one, Seal 2 described above.

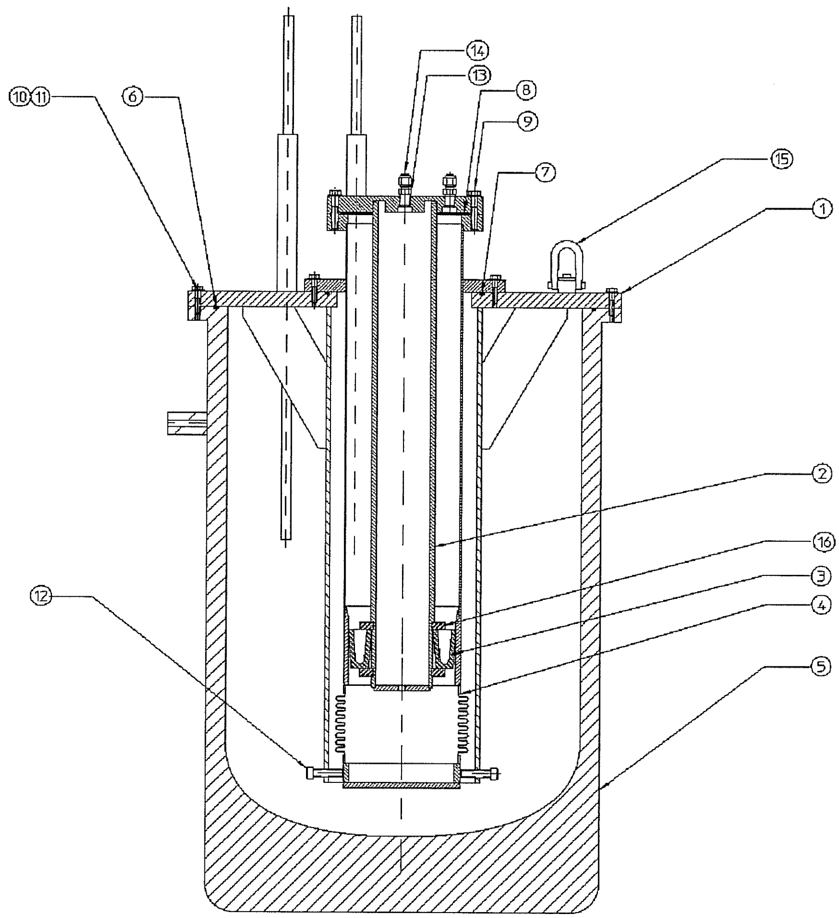


Figure 3.1-1. Seal test rig, 2-"HTS Lead", 3-seal, 4-"DFBX Chimney", 5-LN Dewar, 12 –Screws to give Lateral Offset, 13,14-Ports for GHe.

3.2 Seal 2 Bench Tests

In order to get a rapid indication of whether or not Seal 2 had any promise, we made up a quick test rig using 2 flat flanges as shown in Figure 3.2-1. The seal is loaded with the tensioned studs, each with a stack of Belleville spring washers. The top flange has a swagelock fitting (not shown) which allows us to pressurize the volume inside the seal. The assembly fits into a Liquid Nitrogen dewar, which allows us to submerge it in Liquid Nitrogen. The Belleville spring washers allow us to apply a known load to the seal at room temperature by measuring the deflection of the stack of washers and using the manufacturer's load-deflection data. The Belleville spring washers also ensure that the seal is under load when cooled to LN temperature.

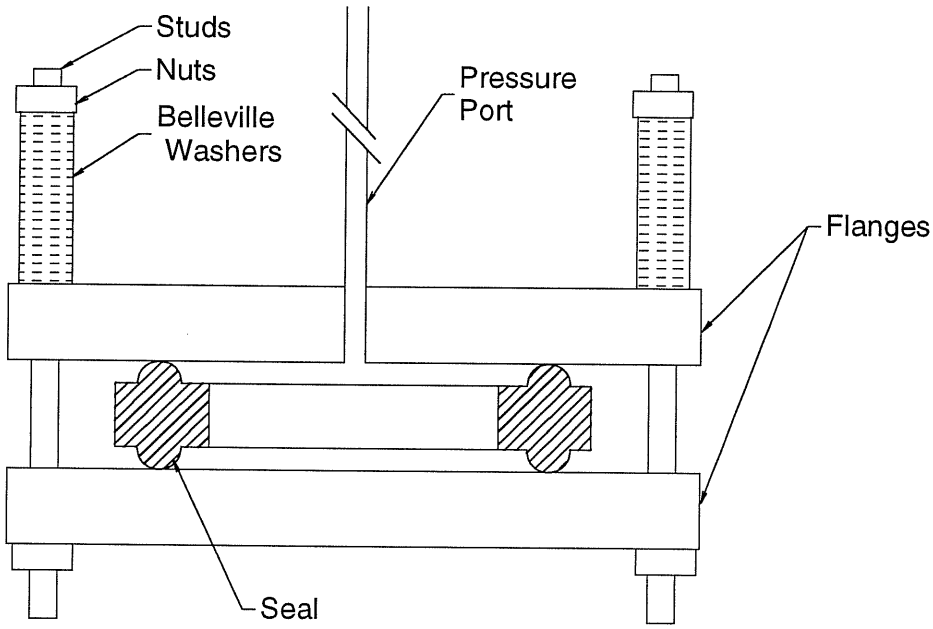


Figure 3.2-1. Bench test fixture with seal 2.

The test procedure is: pressurize the volume enclosed by the seal to 50 psig (3.4 bar gage) with gaseous helium, cool to 77K by covering with Liquid Nitrogen, valve off the helium pressure source, and record the pressure in the trapped volume as a function of time. We did not have an automatic fill or data recording available, so we manually kept the Liquid Nitrogen filled and periodically recorded the reading of the pressure gauge. During the off-shift hours this was done by LBNL maintenance machinists.

The mass flow rate at 77 K is given by

$$\dot{m}_{77K} = \left(\frac{\partial P}{\partial t}\right)_{77K} \times \left(\frac{\partial \rho}{\partial P}\right)_{77K} \times V_{test},$$

where the first term is the rate of pressure drop that we measure, the second term is the dependence of density with pressure that we calculate using HEPAK [2], and the third term is the volume under test. We convert the 77K mass flow rate to a room temperature volumetric flow rate by multiplying the mass flow rate by the specific volume at standard conditions, 6.13 x 10^3 cm^3/g.

The volume under test, including the small diameter tube leading from the rig to the pressure gauge is:

$$V_{test} = \pi(1.67^2) \times 0.75 + \pi(2.245^2) \times 2 \times 0.25 - \pi(0.25^2) \times \pi(4.49) + \pi(0.09^2) \times 36 \text{ in}^3$$
$$V_{test} = 6.57 + 7.92 - 2.77 + 0.92 = 12.64 \text{ in}^3$$
$$V_{test} = 207 \text{ cm}^3 .$$

From HEPAK[2] we find the density to be very nearly linear with pressure over the range 10 to 50 psig, with an average slope of 4.27×10^{-5} g/cm^3-psig.

Table 3.2-1 gives some of the logbook recordings of time and pressure for the two materials. The leak rate is calculated using the above equations.

Table 3.2-1. Bench-Test Results for Seal 2.

Material	300 K Load (lb)	77 K Load (lb)	Date	Time	Pressure (psig)	Leak Rate (atm-cc/sec)
UHMW-PE	2240	1750	7/3/00			no seal
UHMW-PE	5800	4700	7/7/00	13:15	49	
				13:33	33	0.8027
PEEK	5800	5350	7/10/00	13:35	50	
			7/10/00	16:08	41	0.0531
			7/10/00	22:14	31	0.0247
			7/11/00	12:32	21	0.0105
			7/12/00	11:30	15	0.0039
			7/13/00	14:40	12	0.0017
Warm to Room Temperature and Recool to 77 K						
PEEK	5800	5350	7/17/00	12:18	50	
			7/18/00	2:05	40	0.0109
			7/20/00	2:10	30	0.0031
			7/21/00	14:50	27.5	0.0010

The seal manufactured from UHMW-PE material had an unacceptably high leak rate in our tests. Perhaps more load to the seal could have been applied, but we measured significant compression and permanent deformation of the seal, so higher loads probably would not be the answer.

The PEEK seal performed quite well, and the extrapolating measured leak rates to the expected operating differential pressure of 0.1 bar or so (1.5 psig) indicate that the leak rate could be considerably less than the maximum acceptable leak rate of 0.52 atm-cc/sec.

3.3 Initial Seal 2 Leakage Tests

We modified the seal test rig as shown in Figure 3.3-1 to provide a realistic simulation of the PEEK seal as it would be used in the DFBX chamber.

The figure shows the seal (item 3) located between two flanges. The upper flange is attached to item 2, a tube that simulates the current lead, and the lower flange is attached to item 4, which simulates the DFBX current lead chimney. The load on the seal is provided by 6 each ½ inch diameter threaded rods, item 8, which push on the lead through plate, item 21, and spacer blocks, item 22. The upper bellows, item 23, allows the lead to move and tilt in order to ensure that a uniform load is supplied to the seal. Each threaded rod has a stack of Belleville washers with a spherical washer on the top and bottom to allow item 21 to rotate as needed to apply a uniform seal load.

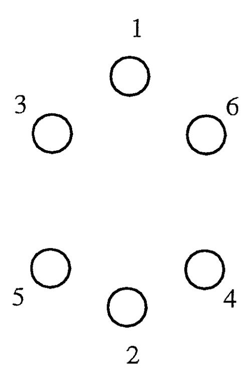
For this simulated setup, the pressurized volume is 380.3 in^3, or 6232 cm^3. The volume on the low-pressure side of the seal is 285.2 in^3 or 4674 cm^3.

The Belleville washers in this test are a series/parallel arrangement of McMaster-Carr model 9713K77 stainless steel Belleville washers with a rating of 573-777 lb for a 0.009 inch deflection. On each threaded rod we have 10 stacks in series; each stack has 2 Belleville washers in parallel.

Figure 3.3-2 (page 11 below) shows the results of deflection-load measurements on this arrangement of Belleville washers. We want the compressive load on the PEEK seal to be about 5000 lb. There are 6 Belleville washer stacks, so if the final compression of the stack is 0.060 inch, the load on each stack is the desired 800 lb. Since the PEEK seal shrinks about 0.010 inch, we require the initial compression of the Belleville stack to be 0.07 inch. The curves show that an initial force of about 1100 lb is needed to obtain a 0.07 inch initial compression of the stack. This load must be reacted by the HTS current lead insulator [1].

The seal was installed in the test rig and the Belleville washers were compressed by 0.070 inches. We found that a reasonable procedure was:

1. Obtain a uniform finger-tight loading on all 6 nuts
2. Take initial height readings of the 6 washer stacks
3. Sequentially tighten the nuts ¼ turn at a time, in the pattern shown below until 0.07 inch compression is achieved



We pressurized the seal to 20.5 psig and observed no pressure drop on the high-pressure side at the end of a 6-day period at room temperature. (Table below.)

Material	300 K Load (lb)	77 K Load (lb)	Date	Time	Pressure (psig)	Leak Rate (atm-cc/sec)
PEEK	6600	N/A	8/11/00	16:15	20.5	
			8/14/00	10:45	20.5	0.0000
			8/15/00	10:00	20.5	0.0000
			8/16/00	8:40	20.5	0.0000
			8/17/00	15:00	20.5	0.0000

The test rig was filled with LN as indicated on Fig 3.3-1. The high-pressure side was pressurized to 20 psig, while the low-pressure side was backfilled with helium gas to nominally 0 psig. During the fill with LN, the pressure on the low side decreased to slightly subatmospheric. The system was allowed to operate automatically overnight, by which time the LN supply dewar was drained. A slight vacuum on the low-pressure side was measured, indicating that the leak, if any, was quite small. The pressure rise was less than 2 in Hg (50 mm Hg or 50 Torr or 1 psi). The data is entered into the table below, and we determine that the measured leak rate is less than 0.026 atm-cc/sec.

Material	300 K Load (lb)	77 K Load (lb)	Date	Time	Pressure (psig)	Leak Rate (atm-cc/sec)
PEEK	6600	4800	8/22/00	18:33	0	
			8/23/00	7:33	1	0.0261

3.4 Voltage Tests

Before we carried out long-term leakage tests, we insulated the region around the seal with Kapton sheets shown on Figure 3.3-1 as items 16 and 24 and additional insulation to prevent arcing around the room temperature flange. Items 16 and 24 consisted of 3 wraps of 0.005 inch thick Kapton film. The region around the seal was flushed by alternately pressurizing to 1.7 bar with pure helium gas and blowing down. This was repeated at least 20 times. The chamber was pressurized to 4.5 psig (1.3 bar abs.) and the voltage of the simulated current lead, item 2 in Fig 3.3-1, was raised using a Bertran Associates Model 375X Hipotter. The leakage current after 60 sec was less than 1×10^{-7} A until breakdown occurred at 2400 V on the first run up and 2500 V on the second run up.

The PEEK seal configuration is therefore adequate to hold off the specified 1500 V.

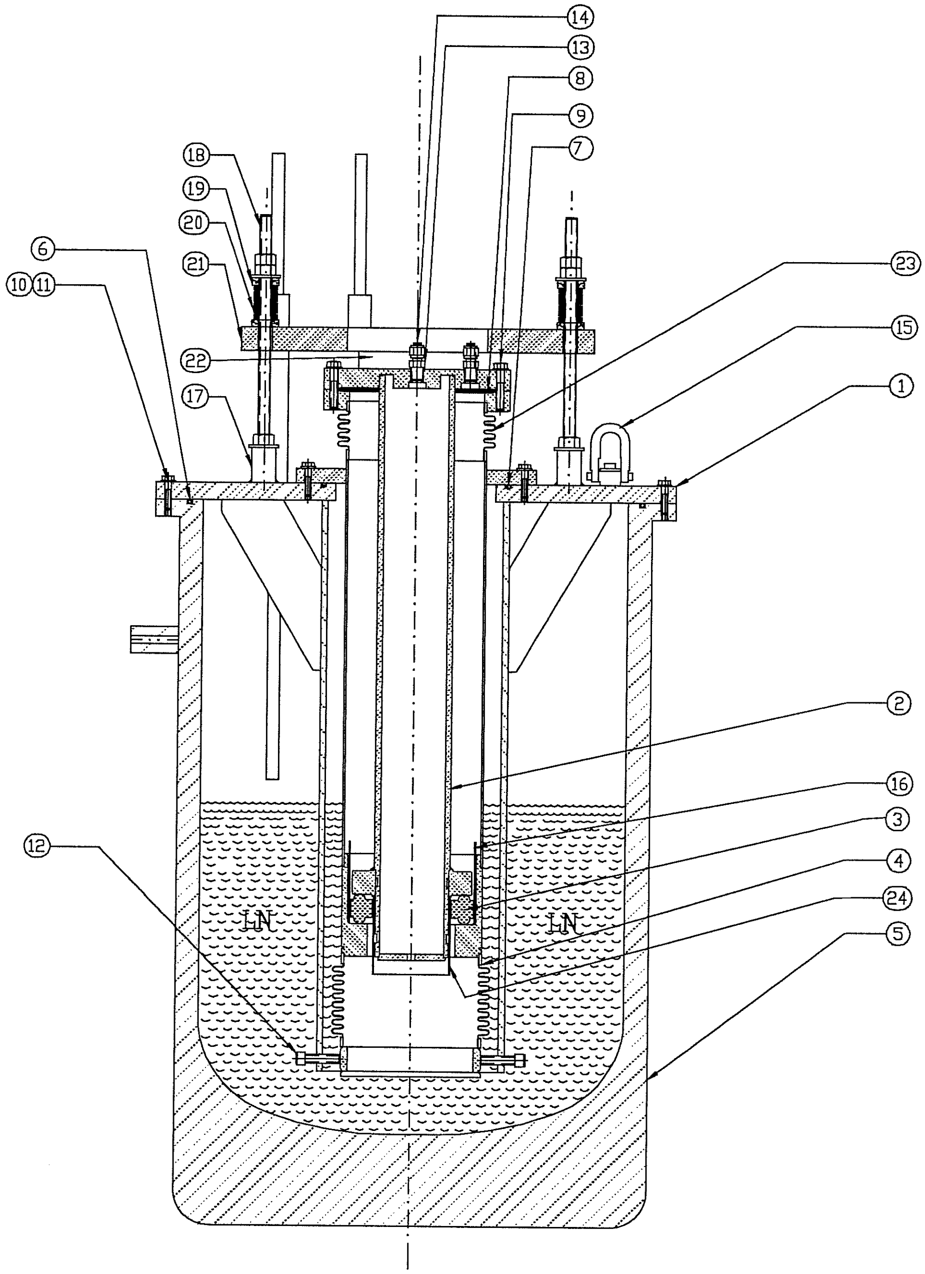


Figure 3.3-1. Test Rig with Seal 2

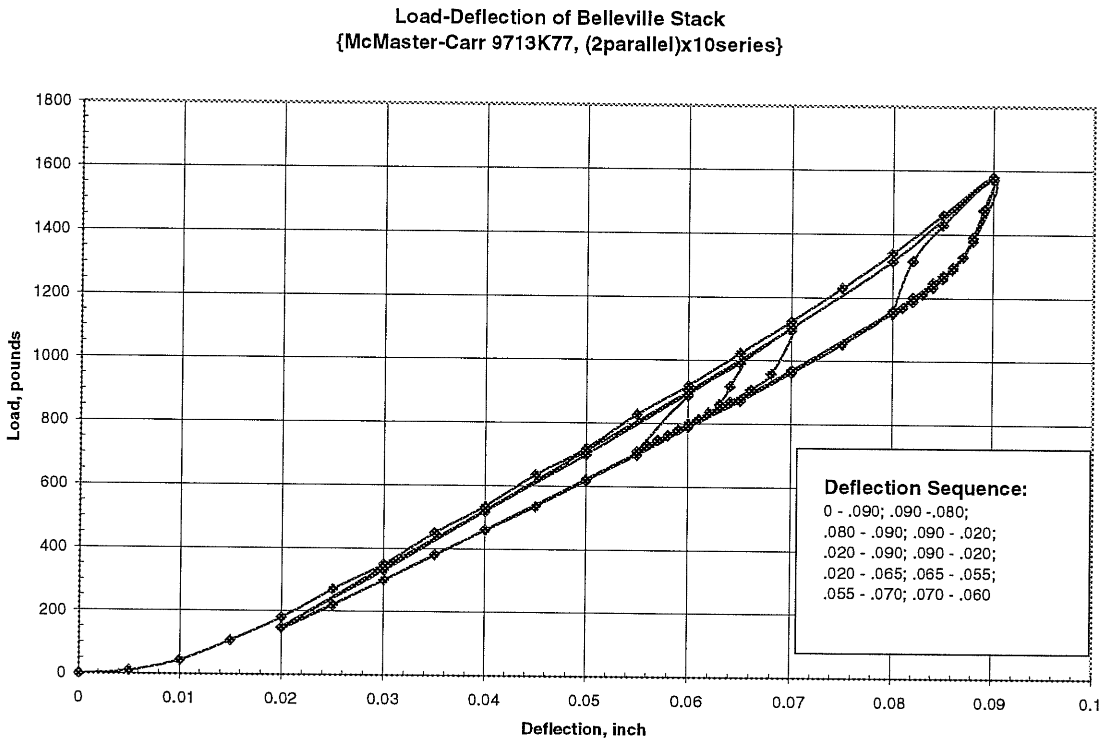


Figure 3.3-2. Measured Deflection-Load Curves for Belleville Washer Stack

3.5 Further Seal Tests

The seal was reloaded into the chamber for additional leakage tests. The bottom of the simulator was deflected horizontally 0.065 inch (1.7 mm) with the bolts shown in Figure 3.3-1 as item 12. This is intended to mock up the deflection expected in the DFBX under operational conditions. The washers were compressed 0.07 inch according to the procedure in 3.3. We used an accumulation technique in this test, in which we applied a nominal 15 psig (2 bar abs) helium pressure to the "20K side of the seal". The other side of the seal forms a closed volume. The LN level was automatically maintained for about 5 days, and at the end of the period the system was allowed to warm and the pressure in the closed volume was measured. The integrated mass flow across the seal is computed from the pressure rise in the trapped volume. The data is given in Table 3.4 below, where the leak rate is estimated to be 0.023 std cm^3/sec. The measured leak rate is much less than the maximum acceptable rate of 0.52 std cm^3/sec.

Table 3.4. Leakage data; lateral offset of 1.7 mm.

Material	300 K Load (lb)	77 K Load (lb)	Date	Time	Pressure (psig)	Leak Rate (std-cc/sec)
PEEK	6600	4800	11/5/2000	12:40	0	
			11/10/2000	12:00	8.2	0.0234

4. Conclusions

The prototype PEEK seal (configuration 2) has been tested and found to satisfy the leakage and voltage requirements.

5. References

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6. Handbook of Cryogenic Engineering, J.G. Weisend II, ed., Taylor and Francis, Philadelphia, PA, USA, 1998, ISBN 1-56032-332-9, p.151-161.